Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 5 February 2008 (MN LATEX style file v2.2)

A radio-emitting outflow in the quiescent state of A0620−00: implications for modelling low-luminosity black hole binaries

E. Gallo[1,2⋆], R. P. Fender[3,4], J. C. A. Miller-Jones[4], A. Merloni[5], P. G. Jonker[6,7,8]
S. Heinz[9,2], T. J. Maccarone[3], M. van der Klis[4]

[1] *Department of Physics, University of California, Santa Barbara, CA 93106, USA*
[2] *Chandra Fellow*
[3] *School of Physics and Astronomy, University of Southampton, Highfield, SO17 1BJ, UK*
[4] *Astronomical Institute 'Anton Pannekoek', University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands*
[5] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, D-85741, Garching, Germany*
[6] *National Institute for Space Research, Sorbonnelaan 2, 3584 CA, Utrecht, The Netherlands*
[7] *Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA*
[8] *Astronomical Institute, Utrecht University, PO Box 80000, 3508 TA, Utrecht, The Netherlands*
[9] *Kavli Institute for Astrophysics Space Research, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA*

5 February 2008

ABSTRACT

Deep observations with the Very Large Array of A0620–00, performed in 2005 August, resulted in the first detection of radio emission from a black hole binary at X-ray luminosities as low as $10^{-8.5}$ times the Eddington limit. The measured radio flux density, of 51 ± 7 μJy at 8.5 GHz, is the lowest reported for an X-ray binary system so far, and is interpreted in terms of partially self-absorbed synchrotron emission from outflowing plasma. Making use of the estimated outer accretion rate of A0620−00 in quiescence, we demonstrate that the outflow kinetic power must be energetically comparable to the total accretion power associated with such rate, if it was to reach the black hole with the standard radiative efficiency of 10 per cent. This favours a model for quiescence in which a radiatively inefficient outflow accounts for a sizable fraction of the missing energy, and, in turn, substantially affects the overall dynamics of the accretion flow. Simultaneous observations in the X-ray band, with *Chandra*, confirm the validity of a non-linear radio/X-ray correlation for hard state black hole binaries down to low quiescent luminosities, thereby contradicting some theoretical expectations. Taking the mass term into account, the A0620−00 data lie on the extrapolation of the so called Fundamental Plane of black hole activity, which has thus been extended by more than 2 orders of magnitude in radio and X-ray luminosity. With the addition of the A0620−00 point, the plane relation provides an empirical proof for the scale-invariance of the jet-accretion coupling in accreting black holes over the entire parameter space observable with current instrumentation.

Key words: black hole physics – ISM: jets and outflows – X-rays:binaries – stars:individual: A0620–00

1 INTRODUCTION

Accretion is widely recognised as the power source for the most luminous sources in the universe; yet only for a relatively narrow range of accretion rates, the energy release by viscous dissipation can be radiated away efficiently by a thin inflow of plasma. While there is little doubt that the thin disc model (cf. Shakura & Sunyaev 1973) captures the basic physical properties of black hole binaries (BHBs) in their thermal dominant (or high/soft) state (see Davis et al. 2005), the accretion mode responsible for the lower-luminosity (low/)hard and quiescent states is still a matter of debate (we refer the reader to Homan & Belloni 2005 and McClintock & Remillard 2006 for thorough reviews, albeit with author-dependent jargon, on X-ray states of BHBs). Since their rediscovery in recent years, radiatively inefficient accretion flows (RIAFs) have been regarded as viable solutions. For very low or very high accretion rates the gas cooling efficiency can drop to a point where most of the dissipated energy is not radiated. Advection-dominated accretion flows (ADAFs; Ichimaru 1977; Narayan & Yi 1994, 1995) are popular analytical models for the dynamics of RIAFs. At low accretion

⋆ elena@physics.ucsb.edu

rates, the plasma density is low enough to inhibit the Coulomb coupling between electrons and ions, such that a significant fraction of the viscously dissipated energy remains locked up in the gas as heat, and is advected inward. In the case of a BH accretor, with no physical surface, such energy would be added to the BH mass as it crossed the event horizon. Under the ADAF working-hypothesis, the relative dimness of quiescent BHBs with respect to quiescent neutron star X-ray binaries has been interpreted as observational evidence for the existence of an horizon in BHBs (Narayan & Yi 1995; Narayan, McClintock & Yi, 1997; Narayan, Garcia, & McClintock 1997; Garcia et al. 2001; McClintock, Narayan & Rybicki 2004; but see Jonker et al. 2006). It has been noted that ADAFs may be convectively unstable under certain viscosity ranges, hence the notion of convection-dominated accretion flows (CDAFs; Quataert & Gruzinov 2000; Narayan, Igumenshchev, Abramowicz 2000), where the inward angular momentum transport by convective motions cancels the outward transport by viscous torques, yielding nearly zero net accretion rate. Blandford & Begelman (1999; 2004) argue that the accreting gas in an ADAF is generically unbound and free to escape to infinity, and elaborate an alternative model, named adiabatic inflow outflow solution (ADIOS). Here the key notion is that the excess energy and angular momentum is lost to a wind at all radii; the final accretion rate into the hole may be only a tiny fraction of the mass supply at large radii, leading to a much smaller luminosity than would be observed from an efficient inflow. Another possible scenario for low-luminosity BHs is that proposed by Merloni & Fabian (2002), where strong, unbound, magnetic coronae are powered by thin discs, with the relative fraction of the power liberated in the corona increasing as the accretion rate decreases. Models in which the X-ray emission would be generated by the coronae of the secondary stars (Bildsten & Rutledge 2000) seem to be inconsistent with the observed spectral shapes and luminosities of quiescent BHB systems (e.g. Kong et al. 2002; Hameury et al. 2003; McClintock et al. 2003).

Regardless of which model provides the correct description for the inflow of gas, in recent years it has become clear that a second component must be taken into account in order to reproduce the broadband spectral energy distribution (SED) of low-luminosity BHBs in the hard and quiescent states (where the–somewhat arbitrary–boundary between the two states can be set around $10^{33.5}$ erg sec^{-1}; McClintock & Remillard 2006). At least down to Eddington-scaled X-ray luminosities of a few 10^{-6}, these systems display flat or slightly inverted radio-mm spectra (Fender 2006 and references therein), interpreted as synchrotron emission from a continuously replenished, partially self-absorbed collimated outflow (cf. Blandford & Königl 1979; Hjellming & Johnston 1988; Kaiser 2006). Such jets may even contribute to the X-ray power-law emission of hard state BHBs by means of optically thin synchrotron and synchrotron self-Compton radiation from the innermost region (Falcke & Biermann 1995; Markoff, Falcke & Fender 2001; Markoff & Nowak 2004; Markoff, Nowak & Wilms 2005; Giannios 2005). Corbel et al. (2003) and Gallo, Fender & Pooley (2003; GFP03 hereafter) have established a quantitative coupling between accretion and the production of jets in hard state BHBs, in terms of a tight correlation between the X-ray and the radio luminosity ($L_{\rm X}$ and $L_{\rm R}$), of the form $L_{\rm R} \propto L_{\rm X}^{0.7\pm0.1}$. The correlation extends over more than 3 orders of magnitude in $L_{\rm X}$ and breaks down around 2 per cent of the Eddington X-ray luminosity $L_{\rm Edd}$, above which the sources enter the thermal dominant state, and the core radio emission drops below detectable levels. Probably the most notable implication of this non-linear scaling is the predicted existence of a critical X-ray luminosity below which a significant fraction of the liberated accretion power is channelled into a radiatively inefficient outflow, rather than being dissipated locally by the inflow of gas and emitted in the form of X-rays (this does not necessarily imply the X-ray spectrum is dominated by non-thermal emission from the jet, as most of the jet power may be stored as kinetic energy). Conservative estimates indicate that such a threshold luminosity should be no lower than $\sim 4\times10^{-5}L_{\rm Edd}$, thereby encompassing the whole quiescent regime (Fender, Gallo & Jonker 2003). The same radio/X-ray scaling found for BHBs holds for super-massive black holes in active galactic nuclei (AGN) when a mass term M is included in the analysis: Merloni, Heinz, Di Matteo (2003; MHdM03 hereafter) and Falcke, Körding & Markoff (2004;FKM04), have independently proven that accreting BHs (the binaries plus a sample of some 100 AGN) form a fundamental plane (FP) in the $\log(L_{\rm R}, L_{\rm X}, M)$ domain (see also Bregman 2005 and Merloni et al. 2006). The FP, for AGN, extends to Eddington ratios as low as 10^{-11}, where the very existence of BHB accretion remains to be proven. In addition, it has been argued that the radio/X-ray correlation might break down somewhere below $10^{-5}L_{\rm Edd}$ (MHdM03; Heinz 2004; Yuan & Cui 2005). In light of these issues, and given the sensitivity limitations of current radio telescopes, deep simultaneous radio and X-ray observations of nearby quiescent systems are needed in order to explore the process of jet formation (if any) in this regime, test the underlying accretion flow models, probe and extend the FP beyond its current limits.

A0620$-$00 (=V616 Mon) was discovered in outburst in 1975 August (Elvis et al. 1975); for about two months, it was the brightest X-ray source in the sky. During the onset of the outburst, the radio counterpart was first detected at a level of 80 mJy at 2.4 GHz (Craft 1975; see Davis et al. 1975 for a previous upper limit). Subsequent observations revealed highly variable radio emission, with a peak flux density of 300 mJy at 1.4 GHz (Owen et al. 1976). Kuulkers et al. (1999) collected all the available radio data for the 1975 outburst (see their Table 1 for a full list of references in chronological order) and found evidence of multiple (at least three) ejection events with expansion velocities in excess of $0.5c$. Within 15 months from the outburst peak, A0620$-$00 had faded back to its quiescent regime, in which it has remained ever since. In 1986 March, McClintock & Molnar (see McClintock, Horne & Remillard 1995) established an upper limit to the radio counterpart in quiescence of 0.14 mJy at 4.8 GHz. Several infrared/optical/UV studies undertaken over the past three decades have determined the system parameters to a high level of accuracy (see Shahbaz et al. 2004 and references therein). Most important for this study, A0620$-$00 lies at a distance of 1.2 ± 0.4 kpc (Shahbaz, Naylor & Charles 1994; Gelino et al. 2001; Jonker & Nelemans 2004) and has a dynamically established BH accretor with mass $M = 11.0\pm1.9\ M_\odot$ (Shahbaz et al. 1994; Gelino et al. 2001). X-ray observations of the system in quiescence, performed with *ROSAT* (McClintock et al. 1995; Narayan, Barret & McClintock 1997), *ASCA* (Asai et al. 1998) and *Chandra* (Kong et al. 2002) have revealed a variable (by a factor of about 2) X-ray source with an average 0.4-2.4 keV luminosity of $\sim 3\times10^{30}$ erg sec^{-1}, corresponding to an Eddington-scaled luminosity of a few 10^{-9}. Due to its low luminosity and relative proximity, A0620$-$00 represents the most suitable known system to probe the FP beyond its current range.

In this Paper we report on deep radio observations of A0620$-$00 performed in 2005 August with the Very Large Array (VLA), observed simultaneously in the X-ray band with *Chandra*, and discuss the implications of their outcomes for modelling low-power accreting BHs.

2 DATA ANALYSIS

2.1 Chandra X-ray observatory

A0620−00 was observed with the back-illuminated S3 chip of the ACIS detector on board *Chandra* on 2005 August 20, starting at Universal Time (UT) 08:36 (MJD 53602.3589), and for ∼39.6 ksec (ObsId 5479). Standard pipeline-processed level 2 data were employed for the analysis, performed using the Chandra Interactive Analysis of Observations (CIAO) software, version 3.2.1.

A0620−00 was detected at right ascension (R.A.) $06^{\rm h}$ $22^{\rm m}$ $44^{\rm s}.54$ and declination (Dec.) -00° $20'$ $44.38''$ (J2000), consistent with the optical position given by Liu, van Paradijs & van den Heuvel (2001). We first searched for background flares by inspecting the 0.3-10.0 keV light curve of the S3 chip, having first subtracted the regions containing sources (8 sources were identified by the *celldetect* tool). Only intervals with count rates between 0.7 and 1.2 count $\sec^{-1}$ (note that the background typically climbs by a factor of 8 between 7-10 keV) were retained for the analysis, resulting in a loss of 0.3 ksec worth of data. Unless otherwise noted, all quoted uncertainties are given at the 90 per cent confidence level.

We extracted data from a circle of 10 pixels in radius centred on A0620−00, and background from an annulus with inner and outer radii of 10 and 18 pixels; 316 counts were detected in the source region (covering an area of ∼314 pixels), and 30 counts in the background annulus (covering an area of ∼704 pixels), yielding a net time-averaged rate of $7.7 \pm 0.5 \times 10^{-3}$ count $\sec^{-1}$ after background subtraction. We then fitted the source light curve with a constant function, and obtained a reduced χ^2 of 0.6, with 13 degrees of freedom (d.o.f.), indicating that no statistically significant variability took place during the observation. The radial profile of the source and that of the normalised Point Spread Function are consistent with each other within the errors, indicating that A0620−00 is a point-like source in the *Chandra* image.

Using the same source and background regions as for the count rate analysis, we extracted the spectrum of A0620−00 over the energy interval 0.3-8.0 keV using the CIAO tool *psextract* (the ancillary response file was automatically corrected for the time-variable low-energy quantum efficiency degradation of the detector). The spectrum was grouped into energy bins containing at least 15 counts and analysed with XSPEC, version 11.2.0. An absorbed power law with photon index $\Gamma = 2.08^{+0.49}_{-0.35}$ provides a good fit to the data. The fitted value of the equivalent hydrogen column density is consistent, within the errors, with the optical value of 1.94×10^{21} cm^{-2} (Predehl & Schmitt 1995), whereas the values obtained by fitting the spectrum with thermal models, such as a bremsstrahlung or blackbody, are significantly lower (in fact they hit the minimum values allowed by the fitting program). The best-fitting model obtained by letting the hydrogen column density free to vary, i.e. the power law model, is shown in Figure 1, over-plotted to the 0.3-8.0 keV *Chandra* spectrum; the parameters are listed in Table 1.

The estimated 2.0-10.0 keV unabsorbed flux is $F_{\rm X} = 4.1^{+0.5}_{-1.4} \times 10^{-14}$ erg cm^{-2} sec^{-1} (the flux error algorithm within XSPEC was set to draw 1000 sets of parameter values from the fitted distribution; the quoted flux uncertainties are given at the 68 per cent confidence level; for reference, the flux over the 0.5-10.0 keV band is $6.7^{+0.8}_{-2.3} \times 10^{-14}$ erg cm^{-2} sec^{-1}). Adopting a distance of 1.2 ± 0.4 kpc, the resulting X-ray luminosity over the 2–10 keV energy interval is $L_{\rm X} = 7.1^{+3.4}_{-4.1} \times 10^{30}$ erg sec^{-1}, where the distance and spectral shape uncertainties contribute similarly to the errors[1]. This corresponds to $\sim 5 \times 10^{-9} L_{\rm Edd}$ for a 11 $M_{\odot}$ BH.

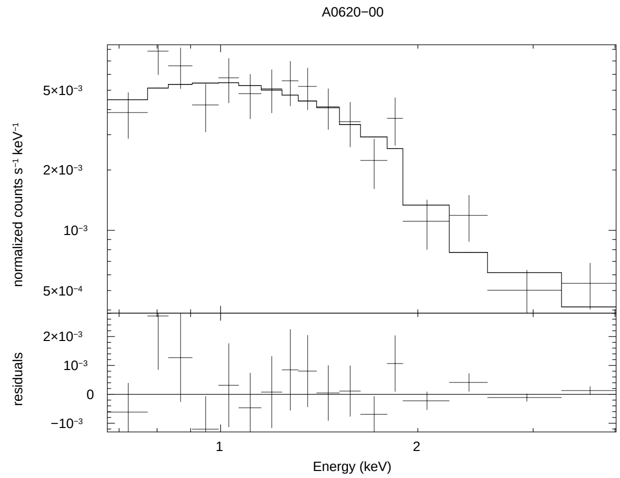

Figure 1. *Top:* X-ray spectrum of A0620−00 as observed by *Chandra* on 2005 August 20. The spectrum is well fitted by an absorbed power law model with photon index $\Gamma = 2.1$ and equivalent hydrogen column density $N_{\rm H} = 1.6 \times 10^{21}$ cm^{-2} (see Table1). The corresponding 2.0-10.0 keV source flux, corrected for absorption, is 4.1×10^{-14} erg cm^{-2} sec^{-1}. *Bottom:* residuals after subtracting the best-fitting model from the data.

The fitted spectral slope is consistent with the results from a previous *Chandra* observation, performed in 2000 February. Kong et al. (2002), applying both CASH statistics and χ^2 statistics to the data, found $\Gamma = 2.19 \pm 0.50$, whereas McClintock et al. (2003) obtained a somewhat softer value ($\Gamma = 2.26 \pm 0.18$) by grouping the data into 10 spectral bins by 12 counts and applying χ^2 statistics. Previous observations with *ROSAT* (Narayan et al. 1997), gave $\Gamma = 3.5 \pm 0.7$, with $N_{\rm H}$ fixed to the optical value. For completeness, we re-analysed the 2000 *Chandra* observation of A0620−00 (ObsId 95) and fitted the sum of the 2000 and 2005 spectra. The extraction of the 2000 spectrum was performed following the same steps as described above; following Kong et al. (2002), only intervals for which the source-free count rate was lower than 0.15 count sec^{-1} were examined. The combined 0.3-8.0 keV spectrum, grouped into bins by at least 15 counts, is well fitted by an absorbed power law with photon index $\Gamma = 2.06^{+0.18}_{-0.25}$ and hydrogen column density $N_{\rm H} = 2.04^{+0.65}_{-0.79} \times 10^{21}$ cm^{-2}. The inferred 2.0–10.0 keV unabsorbed flux is $2.7^{+0.2}_{-0.5} \times 10^{-14}$ erg cm^{-2} sec^{-1} (68 per cent confidence level), corresponding to an average 2.0-10.0 keV luminosity $L_{\rm X} = 4.7 \pm 0.4 \times 10^{30}$ erg sec^{-1}.

2.2 Very Large Array

A0620−00 was observed with the VLA in its C-configuration at a frequency of 8.46 GHz. Three sets of observations were made between 2005 August 19 10:23 UT and 2005 August 20 21:12 UT (MJD 53601.4326–53602.8833), giving a total of 855 min on A0620−00 itself. The *Chandra* observation started about 6 ksec

[1] The quoted uncertainties have been estimated by applying the standard error propagation formulae, being aware that the large fractional errors on both distance and flux formally invalidate the assumptions of small errors behind such formulae. The same caveat applies to the radio luminosity estimate.

Table 1. Best-fitting spectral parameters of A0620−00 as observed by *Chandra* on 2005 August 20. All quoted uncertainties are at the 90 per cent confidence level. The goodness of the fit is expressed by the reduced χ^2 for a certain number of degrees of freedom (d.o.f.).

Model	$N_{\rm H}$ (10^{21} cm^{-2})	Γ	kT (keV)	$\chi^2_{\rm red}$/d.o.f.
Power law	$1.62^{+1.51}_{-1.36}$	$2.08^{+0.49}_{-0.35}$	...	0.83/14
	1.94 (fixed)	2.17±0.27	...	0.80/15
Bremsstrahlung	$0.64^{+1.33}_{-0.64}$	...	$3.46^{+6.62}_{-1.65}$	0.88/14
	1.94 (fixed)	...	$2.06^{+1.09}_{-0.59}$	0.99/15
Blackbody	$0.00^{+0.05}$	...	0.46±0.06	1.68/14
	1.94 (fixed)	...	0.39⋆	2.39/15

⋆ No error is calculated for reduced χ^2 higher than 2.

before the last VLA set, meaning that for the remaining 33.6 ksec the X-ray/radio coverage was strictly simultaneous.

VLA Data calibration and imaging were performed using standard procedures within the National Radio Astronomy Observatory's (NRAO) ASTRONOMICAL IMAGE PROCESSING SYSTEM (AIPS). 3C 48 was used as the primary calibrator, using the flux density scale derived at the VLA in 1999 as implemented in the 31Dec05 version of AIPS. The secondary calibrator was J 0641−0320, at an angular separation of 6.03° from the target source, with an 8.4-GHz flux density of 0.639 ± 0.001 Jy. 15-min observations of A 0620−00 were interleaved with 90-sec observations of the phase calibrator. The observations were made using standard procedures, with two IF pairs of width 50 MHz centred at 8.435 and 8.485 GHz.

Figure 2 shows a naturally weighted contour map of the observed field. An unresolved (down to a beam size of $3.7'' \times 3.2''$) radio source is visible at a position consistent with A0620−00, whose X-ray position is marked with a cross. The fitted radio source position is R.A. $06^{\rm h}22^{\rm m}44.503^{\rm s}\pm0.012^{\rm s}$ Dec. $-00^{\rm d}20'44.72''\pm0.10''$ (J2000). The source is detected at a flux density $S_{8.46\ \rm GHz} = 51.1\ \mu$Jy beam^{-1}, a 7.3σ detection at the rms noise level of 7.0 μJy bm^{-1}; the quoted noise level is a factor 1.4 higher than the theoretical thermal noise limit, possibly because the source was too weak to use self-calibration.

In order to quantify the probability that the detected radio flux is extragalactic in origin, we made reference to the catalogue of published source counts at 1.4 GHz in the literature, complete down to 50 μJy (Huynh et al. 2005). Integrating their polynomial fit to the differential source counts from a minimum value (see below) up to 'infinity' (that is 1000 Jy for practical purposes), gives the number of counts expected per square arcsec. Using a minimum flux density of 147 μJy, which is the 1.4 GHz flux density corresponding to 50 μJy for a non-thermal spectrum typical for extragalactic radio sources, where the monochromatic flux density, S_ν, scales as ν^α, with $\alpha = -0.6$, gives a probability of 6×10^{-5} of having an extragalactic background source within the same distance of the X-ray position as our radio source. This effectively rules out an extragalactic origin for the detected emission.

At a distance of 1.2±0.4 kpc, the measured flux corresponds to a radio luminosity $L_{\rm R} = 7.5 \pm 3.7 \times 10^{26}$ erg sec^{-1}, with the quoted error bar being dominated by the distance uncertainty. In approximating the integrated radio luminosity as the monochromatic luminosity multiplied by the observing frequency, we have assumed a flat radio spectrum of spectral index $\alpha = 0$, as is usually observed in the hard X-ray state of BHBs, with a spectrum extending up to $\nu_{\rm max} = 8.46$ GHz (see Section 3 for details on the interpretation of the radio emission). The integration is performed between this upper bound and minimum frequency $\nu_{\rm min} \ll \nu_{\rm max}$. However, it is important to mention that several hard state sources, such as XTE J1118+480 (Fender et al. 2001), GX339–4 (Corbel et al. 2000), XTE J1550–564 (Corbel et al. 2001), actually display inverted radio-mm spectra, with $\alpha \simeq +0.5$, or even higher, up to $+0.7$ over some epochs. If this was the case in A0620−00 , this would introduce a further source of error in the luminosity estimate, although negligible with respect to the distance uncertainties.

The two bright sources to the north and northeast of A0620−00 are of similar brightness to the source itself. The parameters of all three sources are given in Table 2. The two northern sources are separated from one another by 16.4″. The 2MASS catalogue shows no obvious match to the northern sources, and no central source between the two (as might be expected if they were associated with the lobes of a radio galaxy). If they are extragalactic, the possibility arises of using them to measure the proper motion of A0620−00.

3 RADIO EMISSION IN QUIESCENCE

One of the main questions we wish to address in this work concerns the hard state jet survival at low quiescent luminosities. The deep VLA observations presented here provide us with the first detection of radio emission from a BHB at $L_{\rm Edd} \simeq 10^{-8.5}$, 3 orders of magnitude deeper than any detection reported so far. The measured radio flux represents the lowest level of radio emission, both in flux and luminosity, ever reported for an accreting BH. Prior to these observations, the lowest Eddington-scaled X-ray luminosities for which radio emission had been detected from a BHB were between a few 10^{-6} to about 10^{-5}, respectively in V404 Cyg and GX 339–4 (Gallo et al. 2005; Corbel et al. 2003). Since neutron star X-ray binaries tend to be dimmer in the radio band (Migliari & Fender 2006), the measured radio flux is actually the lowest reported for a Galactic X-ray binary system. We point out that the radio detection of A0620–00, which is among the dimmest BHBs detected in X-rays so far (e.g. McClintock et al. 2003; Tomsick et al. 2003), really pushes the performances of current radio telescopes to the limit. For comparison, GS 2000+25, whose quiescent X-ray luminosity is a factor of about 2 lower than A0620−00 (Garcia et al. 2001) is located at a distance of 2.7 kpc (Jonker & Nelemans 2004 and references therein). If its radio luminosity was comparable to that of A0620–00, it would take 8×12 hr on source for the VLA in order to get a 5σ detection. The next generation of radio arrays, such as e-MERLIN and EVLA, will be able to achieve this sensitivity in about 7 hr.

As far as the interpretation is concerned, the synchrotron na-

Table 2. Parameters of the three radio sources in Figure 4.

Source	RA (J 2000)	Dec. (J 2000)	Flux density (μJy bm^{-1})
A0620−00	$06^{\rm h}22^{\rm m}44.503^{\rm s}\pm0.012^{\rm s}$	$-00^{\rm d}20'44.72''\pm0.10''$	51.1 ± 6.9
N source	$06^{\rm h}22^{\rm m}44.577^{\rm s}\pm0.018^{\rm s}$	$-00^{\rm d}19'59.03''\pm0.20''$	43.0 ± 6.9
NE source	$06^{\rm h}22^{\rm m}45.295^{\rm s}\pm0.014^{\rm s}$	$-00^{\rm d}20'11.44''\pm0.23''$	52.2 ± 6.7

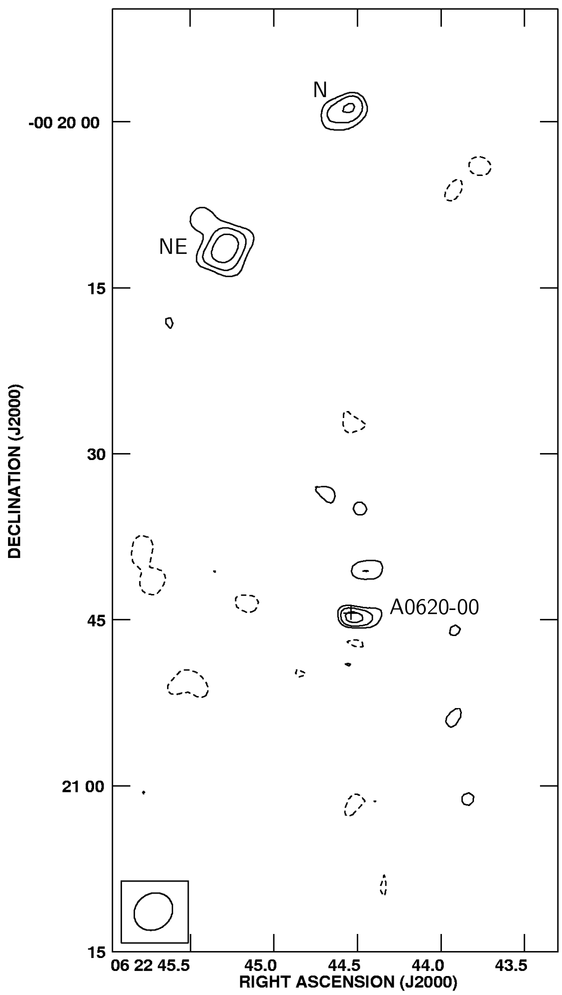

Figure 2. Radio contour map of the field surrounding A0620−00 as observed by the VLA on 2005 August 19-20; the *Chandra* position of A0620−00 is marked with a cross, whose size corresponds to the error on the X-ray position. The beam size is $3.7'' \times 3.2''$, and the rms noise in the image is 7.0 μJy bm^{-1}. Solid and dashed contours are at $\sqrt{2}^n$ and $-(\sqrt{2}^n)$ times the lowest contour level of 20 μJy bm^{-1}. In addition to A0620−00, we detect two other sources to the north (Table 2).

ture of the radio emission from X-ray binaries is generally inferred from the high brightness temperatures, high degree of polarisation and non-thermal spectra, whereas the outflowing nature is inferred by brightness temperature arguments, combined with the persistent level of radio emission (Hjellming & Han 1995; Mirabel & Rodríguez 1999; Fender 2006). As in the case of A0620−00 we have none of the above-mentioned features at our disposal, we must explore different mechanisms as well. Fitting the infrared-to-X-ray spectrum of A0620−00 in quiescence with a pure ADAF model severely under-predicts the measured radio flux: the extrapolation of an (admittedly old version of an) ADAF spectrum for A0620−00 down to radio frequencies underestimates the 8.5 GHz flux by more than 3 orders of magnitude (see Narayan McClintock & Yi 1996). Despite the significant improvements in the ADAF model over the past decade, to take into account effects such as the possible energy advection by electrons and substantial wind mass loss, it seems unlikely that the radio to X-ray spectra of hard and quiescent states can be reproduced without invoking an extra component. Even though various models for the quiescent state of BHBs predict a substantial fraction of the inflowing gas be lost to a wind, far too high mass loss rates would be required in order to reproduce the measured radio fluxes in terms of e.g. free-free emission (see Gallo, Fender & Hynes 2005, and references therein, for a more quantitative argument applied to V404 Cyg).

At such low luminosity levels we must also explore the possibility that the radio emission may be contaminated by gyro-synchrotron radiation from the corona of the companion star. The secondary star in A0620−00 is a 0.7 $M_{\odot}$ K3-K4V star, in a 7.75 hr orbit around the BH. Being in forced synchronous rotation, it will be a very fast rotator; the observed rotational broadening of the spectral lines of the companion star, together with an estimate of the inclination, gives a velocity $v \simeq 130$ km sec^{-1} (Marsh, Robinson & Wood 1994; Shahbaz et al. 1994; Gelino, Harrison & Orosz 2001). Typical radio luminosities from early-to-mid type K stars vary in the range 1×10^{14} up to 3×10^{15} erg sec^{-1} Hz^{-1} in the most extreme cases. HD 197890 (Speedy Mic), a rapidly rotating single K star, with orbital period of 0.42 days and $v \times \sin(\mathrm{i}) \simeq 170$ km sec^{-1}, has a radio luminosity of 2.7×10^{15} erg sec^{-1} Hz^{-1} at 8.4 GHz (Robinson et al. 1994). AB Dor, a similar object also with period of about half a day, has been detected at about 5 mJy (Lim et al. 1994). At a distance of 15 pc, this implies $L_{\rm R} \simeq 1.4 \times 10^{15}$ erg sec^{-1} Hz^{-1}. Note that the orbital parameters have been proven not to influence significantly the level of radio emission from magnetically active stars (Drake, Simon & Linsky 1989; see Güdel 2002 for a thourough review). In fact, radio emission from tight binary star systems is significantly weaker than that of RS CVn binaries or magnetically active single stars, possibly because of reduced differential rotation, weaker dynamo effects or a change in the energy transfer mechanism. As the measured radio emission from A0620−00 is a factor of 30 higher than the highest radio luminosities for magnetically active stars of comparable spectral type, we conclude that such a contamination is likely to be negligible.

Radio emission from A0620−00 is also unlikely to be associated with a major optically thin radio flare, as such phenomena in BHBs tend to be bright ($>$ mJy), short-lived (few hr timescales) and have always been associated with outbursts at all wavelengths[2].

[2] but see Pal & Chakrabarti (2004) who claim the detection of a $\sim$190 sec

Radio emission from radio lobes presumably resulting from the interaction of highly relativistic ejecta with the surrounding interstellar medium, of the kind observed in e.g. 1E1740.7–2942 (Mirabel et al. 1992; 1993), GRS 1758–258 (Mirabel et al. 1993), Cyg X-1 (Gallo et al. 2005), are typically observed on much larger (arcmin) scales. Thus we are led to the conclusion that the quiescent radio emission is probably generated in a continuously replenished relativistic outflow, associated with a persistent level of radio emission and flat or inverted radio-mm spectrum (however, this does not necessarily rule out short time-scale variability, of the kind observed in V404 Cyg; Hynes et al. 2004a). As for V404 Cyg, only high sensitivity, high spatial resolution radio observations will ultimately answer the question of whether the radio emitting outflow is collimated at such low flux levels.

It has been suggested that the outflow, and not the inflow of gas, could be responsible for the hard X-ray power law which dominates the spectrum of hard state BHBs (Falcke & Bierman 1995; Markoff et al. 2001; Giannios 2005). In response to the criticism offered by several authors (e.g. Zdziarski et al. 2003; Heinz 2004; Maccarone 2005), the jet model has also been significantly improved over the past years. In a recent work, Markoff, Nowak & Wilms (2005) explore the possibility that the jet 'base', i.e. a hot wind blowing away from the inner regions of the accretion flow, and is later collimated into the actual jet, in fact coincides with the Comptonising corona itself. Here the radio-to-soft X-rays are dominated by synchrotron emission, while the hard X-rays are due to inverse Compton scattering at the jet base/corona, with both disc and synchrotron photons acting as seed photons. The authors find that the jet and Compton coronal models describe high statistics observations of GX 339–4 and Cyg X-1 while in the hard state equally well. At least in one source (GX 339–4), the pure-jet model is able to reproduce analytically the slope of the observed radio/X-ray correlation (Corbel et al. 2003) by varying the fractional jet power (Markoff et al. 2003). It would be interesting to see whether the same model could account for the SED of quiescent BHB systems as well; this will be explored in a future paper.

Yuan, Cui & Narayan (2005) developed a coupled jet-ADAF model for the SED of XTE J1118+480 while in the hard X-ray state (see also Meier 2001). Unlike in the model by Markoff and collaborators, here the X-ray emission is still dominated by a highly advective inflow, while the outflow emission is modelled by means of multiple internal shocks in a mildly relativistic highly collimated jet. The model also seems to account for the complex timing behaviour and optical/X-ray time lags observed in this source (Kanbach et al. 2001; Malzac et al. 2003). It is worth mentioning that, within this framework, the estimated outer accretion rate is about one tenth of Eddington, comparable to the values inferred in the thermal dominant state BHs. In any case, the model generalisation (Yuan & Cui 2005) predicts that the observed radio/X-ray correlation in hard state BHBs (GFP03) should break down at low quiescent luminosities. This is not observed, as discussed in Section 3.1.

3.1 A0620−00 and the Radio/X-ray/Mass correlations

The simultaneous *Chandra*/VLA observations of A0620–00, together with the dynamical estimate of the BH mass in this system, allow us to test and extend the FP of BH activity (MHdM03; FKM04) orders of magnitude beyond its current limits. We wish to stress that the only way this can be done is to probe the low luminosity, low-mass corner of the distribution (i.e. to the left of the plane as viewed edge-on in Figure 4 of MHdM03). This is because the right hand side of the relation is already occupied by the most massive BHs we know, accreting at around the Eddington rate.

With the addition of the A0620−00 data, the sample of MHdM03 (the only genuinely beamed source, 3C 273, has been removed from the original sample; see Merloni et al. 2006) is well fitted by the same expression given in the original paper: $\log L_{\rm R} = (0.6\pm0.1)\log L_{\rm X} + (0.8\pm0.1)\log M + (7.3\pm4.1)$. The logarithmic deviation from the FP is 0.93σ, within even the measurement error. The validity of the FP is thus extended by 2.5 orders of magnitude in $L_{\rm X}$ and 2.3 orders of magnitude in $L_{\rm R}$. Figure 3 shows the FP, with the A0620−00 point marked by a triangle in the bottom left corner. We note that the current estimate of the BH mass in A0620−00 (Gelino et al. 2001) is based on the assumption that the accretion disc does not contaminate the IR emission from the system, whereas recent observations show that a disc contamination is, at least sometimes, present (Hynes, Robinson & Bitner 2005). This would result in a lower BH mass. For reference, assuming 5 $M_\odot$ for the mass of the BH in A0620−00 would in result in a χ^2 compared to the mean of 0.51 (vs. 0.18 for $M = 11\ M_\odot$).

This 3D correlation has led to two different proposals for unifying low-power BHs. While FKM04 argue that the plane relation follows naturally from a model in which the X-ray emission from sub-Eddington BHs (hard and quiescent systems in the case of the binaries) is dominated by optically thin synchrotron radiation from the innermost region of the jet (cf. Falcke & Bierman 1995), MHdM03 apply the theoretical relations by Heinz & Sunyaev (2003), and conclude that the FP is inconsistent with the X-ray emission coming from a radiatively efficient inflow and is only marginally consistent with optically thin synchrotron from the jet. In a refined analysis which includes a proper treatment of the electrons' cooling, Heinz (2004) concludes that X-ray synchrotron emission would be as unlikely as efficient disc emission. As discussed at length by both groups in a recent work (Merloni et al. 2006), while the measured slope of the FP may depend on the sample selection, the agreement between the slopes for the BHB and for the AGN sample indicates that the slope uncertainty cannot exceed by much that quoted in the original papers. However, it remains true that, within those errors, there is margin for both models (RIAF-plus-jet or pure-jet) to be accepted (but see Körding, Falcke & Corbel 2006, who argue that using hard state objects alone, the plane relation is in agreement with the prediction of a pure jet model for the emitted radiation). It is worth mentioning that Roberston & Leiter (2004) propose a radically different explanation for the plane relation, in terms of a magnetic propeller effect that requires intrinsically magnetic central compact objects.

In light of these issues, while it may be still premature to use the FP to constrain the accretion flow model, the A0620−00 data (minus 3C 273) – with $\log(L_{\rm X}) = 30.84$, $\log(L_{\rm R}) = 26.87$ and $\log(M) = 1.04$ – confirm that a scale-invariant description of the jet-accretion coupling is supported by observations of accreting (candidate) BHs spanning *fourteen* orders of magnitude in $L_{\rm X}$, *fifteen* orders of magnitude in $L_{\rm R}$, and *eight* orders of magnitude in M.

For completeness, we also re-fitted[3] the BHB sample of

micro-flare, with peak flux of 3.84 mJy at 1.28 GHz, during a 1 hr long observation of A0620−00 with the Giant Meter Radio Telescope in 2002.

[3] As in GFP03, only data up to 2.5 Crab (scaled to 1 kpc) were fitted, with the exclusion of Cyg X-1.

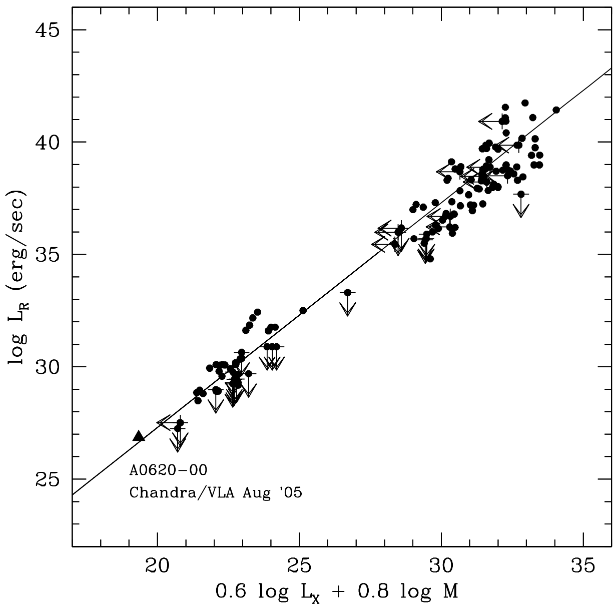

Figure 3. The Fundamental Plane (FP) of black hole activity of Merloni, Heinz & Di Matteo (2003; see also Falcke, Körding & Markoff 2004) with the addition of A0620−00. Thanks to the simultaneous *Chandra*/VLA detection of this system, marked by a triangle, the FP is extended by more than two orders of magnitude on the x-axis.

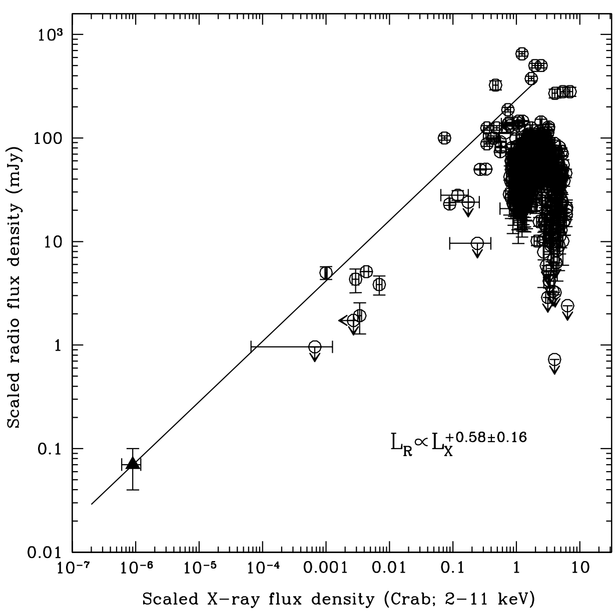

Figure 4. The BHB sample of Gallo, Fender & Pooley (2003), with the addition of the A0620−00 *Chandra*/VLA data. The hard state sources – below a flux of 2.5 Crab, scaled to a distance of 1 kpc – are well fitted by a non linear radio/X-ray relation of the form $L_{\rm R} \propto L_{\rm X}^{0.58\pm0.16}$ (solid line), implying that the ratio between the radio and X-ray luminosities tends to increase towards quiescence. The fitted slope is admittedly affected by the uncertainties in the distance to GX 339–4 (see text); the quoted value is given for D=6 kpc.

GFP03 with the addition of the A0620−00 data. The large uncertainties in the distance to GX 339–4 (Hynes et al. 2004b), for which the correlation holds over 3 orders of magnitude in $L_{\rm X}$, affect the fitted slope. Assuming a distance of 6 kpc to this source (instead of 4 kpc adopted in the original paper, before Hynes et al. 2004b), results in $L_{\rm R} \propto L_{\rm X}^{0.58\pm0.16}$ (see Figure 4). Adopting instead the (less likely) maximum distance of 15 kpc gives a slope of 0.68 ± 0.03. The fitted slopes are consistent with each other within the errors, and with the 0.7 ± 0.1 given by GFP03. We note however that a slope of 0.71 ± 0.01 was first found between the radio and X-ray *fluxes* in GX339–4 (Corbel et al. 2003) over different epochs and accretion regimes. The same slope, albeit with larger errors, was later found for V404 Cyg (GFP03). This might indicate a flattening of the correlation at very low luminosities. It is worth mentioning that the low-luminosity Galactic Centre BH, Sagittarius A*, appears to lie well above the fundamental plane when in the non-X-ray-flaring regime (see Markoff 2005). Pending a more accurate determination of the actual slope value, a *non linear* radio/X-ray scaling for hard state BHBs appears to hold over 6.5 orders of magnitude in X-ray luminosities, between $10^{-8.5}$ to a few $10^{-2} L_{\rm Edd}$. Above this critical luminosity, and allowing for hysteresis effects (Maccarone & Coppi 2003), the systems make a transition to the thermal dominant state, and their core radio emission is quenched below detectable levels. This latter point clearly highlights a further level of complexity, which is not apparent when the BHB and AGN samples are blended (see however Maccarone, Gallo & Fender 2003, and Greene, Ho & Ulvestad 2006, who suggest that a partial quenching of radio emission from AGN takes place in the same Eddington-scaled luminosity interval as for the binaries). The criticism by Bregman et al. (2005) does not apply to BHB systems, the argument there being that one should restrict the study to a sample of objects for which the range in the distance squared is less than that in $L_{\rm R}$ or $L_{\rm X}$ in order to find meaningful relations. Not only the range in distance squared for the binaries is less than 4 orders of magnitude smaller with respect to that in $L_{\rm X}$, but also the correlation has been shown to hold for two different sources over a period of several years (Corbel et al. 2003; GFP03). We refer the reader to Merloni et al. (2006) for a fuller discussion on the robustness of the FP.

4 ASSESSING THE OUTFLOW CONTRIBUTION TO THE GLOBAL ENERGETICS AND DYNAMICS

Prior to this work, two major uncertainties concerned: 1. whether quiescent BHBs are still producing radio emitting outflows in quiescence; 2. if so, whether the same non-linear radio/X-ray scaling found in hard state sources holds down to very low luminosities. Nearly simultaneous radio/X-ray observations of the BHB XTE J1908+094 during the decay of an outburst (Jonker et al. 2004) suggested that the radio/X-ray correlation might break down at low luminosities – caveat the not strict simultaneity of those observations combined with the very fast decay rate. However, the A0620−00 data imply a positive answer to both questions. If the radio/X-ray relation does break down at some point, as has been suggested on the basis that the synchrotron X-rays from the jet scale more slowly with the accretion rate than the X-ray flux from the accretion flow (e.g. Heinz 2004), this does not happen down to at least $10^{-8.5} L_{\rm Edd}$. This appears to be at odds with the prediction by Yuan & Cui (2005), whose coupled ADAF-jet model predicts that the correlation should turn and become steeper (assuming the form $L_{\rm R} \propto L_{\rm X}^{1.23}$) somewhere below 10^{-5} to $10^{-6} L_{\rm Edd}$.

The confirmation of a non-linear radio/X-ray scaling down to low quiescent luminosities lends observational support to the notion of ‘jet-dominated states’ as defined by Fender et al. (2003), i.e. a regime in which the energy carried off by an outflow – in the form of radiation, kinetic energy and Poynting flux – exceeds the X-ray power output (notice that this is not necessarily the same proposal by Falcke & Bierman, 1995; 1996; 1999, where the *radiation* output is jet-dominated, and the underlying inflow is even dimmer than in e.g. the ADAF picture). This notion follows from the non-linear radio/X-ray scaling under the *assumption* that the total power output from hard/quiescent state X-ray binaries is the sum of the radiative luminosity of the flow and total jet power, i.e. that no extra ‘missing energy’, most notably advection, is needed in order to reproduce the observed low X-ray luminosities. At the same time, while ADAF models predict the existence of bipolar outflows emanating from the surface layers of the equatorial inflow (see Narayan & Yi 1995), generally they do not address the importance of such outflows with respect to the overall accretion process in terms of energetics.

Having established the presence of a radio-emitting outflow in the quiescent state of A0620–00, in the following we shall attempt to test whether its contribution can be relevant to the flow energetics and dynamics, under two representative working-hypotheses: ADAF vs. ADIOS. The boundary condition of the problem is set by the accretion rate in the outer disc of A0620−00 during quiescence, $\dot{M}_{\rm out}$. Based on models for the optical/UV emission of the outer accretion disc in dwarf novae (Warner 1987), corrected downward to account for the mass difference, McClintock et al. (1995) estimate $\dot{M}_{\rm out} = y 10^{-10} M_{\odot}$ yr^{-1} for A0620–00, where y is a factor of the order unity, that can be up to a few. This value is also comparable to the 3×10^{-11} $M_{\odot}$ yr^{-1} (e.g. Huang & Wheeler 1989) inferred from the measure of the total energy released during the 1975 outburst of A0620−00 adopting 58 year recurrence time based on plate archives which showed an outburst in 1917 (Eachus et al. 1976). This time-averaged value had been calculated based on a distance of 1 kpc for A0620−00 (vs. a refined value of 1.2 kpc) and could still be underestimated by a factor 2 or so, to allow for the possibility that an intermediate outburst was missed[4].

The putative luminosity associated with $\dot{M}_{\rm out}$, if it was to reach the black hole with standard radiative efficiency, would be

$$L_{\rm tot} \equiv \eta \dot{M}_{\rm out} c^2 \simeq 6 \times 10^{35} y \; (\eta/0.1) \; {\rm erg \; sec^{-1}} \quad , \qquad (1)$$

much larger than the observed X-ray (or bolometric) luminosity. In the above formula η is the accretion efficiency, which depends only on the BH spin. The various RIAF models provide different explanations for the much lower luminosities that are observed in terms of different ‘sinks’ for the energy.

(i) In the **ADAF** scenario, it is assumed that all the $\dot{M}_{\rm out}$ is accreted onto the black hole ($\dot{M}_{\rm in} = \dot{M}_{\rm out}$) while the radiated luminosity $L_{\rm bol} = \epsilon_{\rm rad} \dot{M}_{\rm in} c^2$ is much smaller as a result of a reduced radiative efficiency

$$\epsilon_{\rm rad} \equiv \eta f(\alpha) = \eta \times \left\{ \begin{array}{ll} 1, & \dot{M}_{\rm out} \geq \dot{M}_{\rm cr} \\ (\dot{M}_{\rm out}/\dot{M}_{\rm cr})^{\alpha}, & \dot{M}_{\rm out} < \dot{M}_{\rm cr} \end{array} \right. \qquad (2)$$

where $\dot{M}_{\rm cr}$ is the critical rate above which the disc becomes radiatively efficient. The index α is typically close to unity, but its exact value may depend on the micro-physics of ADAF and on how the bolometric luminosity is calculated (for example, MHdM03 found that, if $L_{\rm bol}$ is estimated from the 2–10 keV luminosity with a constant correction, then $\alpha \simeq 1.3$; but see Yuan & Cui 2005 for a different scaling). Writing the bolometric luminosity of A0620−00 as $L_{\rm bol} = w \; 10^{32}$ erg sec^{-1}, where we have introduced a multiplicative factor w, we have that

$$f(\alpha) = \left(\frac{\dot{M}_{\rm out}}{\dot{M}_{\rm cr}} \right)^{\alpha} \simeq 1.7 \times 10^{-4} \; (w/y) \; (0.1/\eta). \qquad (3)$$

For $\alpha = 1.3$,

$$\dot{M}_{\rm cr} \simeq 8 \times 10^{-8} \; y^{(1+1/1.3)} \; w^{(-1/1.3)} \; (\eta/0.1)^{(1/1.3)} \; M_{\odot} \; {\rm yr}^{-1} \qquad (4)$$

which corresponds to an Eddington-scaled critical accretion rate $\dot{m}_{\rm cr} \simeq 0.36 \; y^{(1+1/1.3)} w^{(-1/1.3)} (\eta/0.1)^{(1+1/1.3)}$. With $w \sim 5 - 10$, as implied by the ADAF spectral modelling (see Figures 6 and 7 in Narayan et al. 1997), a self-consistent ADAF solution is obtained for $\dot{m}_{\rm cr}$ of a few times 10^{-2}, as expected on theoretical grounds.

Contrary to the ADIOS case, for the ADAF scenario to be self-consistent, the total kinetic power of the jet/outflow, $L_{\rm kin}$, should be a negligible fraction of $L_{\rm tot}$. In order to verify this, we can estimate $L_{\rm kin}$ making use of the normalisation for the jet kinetic power vs. radio luminosity derived by Heinz & Grimm (2005). Obviously, if this number is high enough, the jet contribution to the flow energetics (and dynamics) can be negligible with respect to advective cooling. In Heinz & Grimm (2005) the radio core emission of three well studied radio galaxies (M87, Per A and Cyg A) was directly compared to the radio lobe emission, used a jet calorimeter. They proposed that the jet kinetic power can be estimated from the core radio luminosity in the following way:

$$L_{\rm kin} = 6.2 \times 10^{37} \left(\frac{L_{\rm R}}{10^{30} {\rm erg \; s^{-1}}} \right)^{\frac{1}{1.4 - \alpha_r/3}} \mathcal{W}_{37.8} \; {\rm erg \; sec^{-1}} \qquad (5)$$

where α_r is the radio spectral index, and the parameter $\mathcal{W}_{37.8}$ carries the (quite large) uncertainty on the radio galaxy calibration[5]. For A0620−00 , assuming a flat radio spectral index $\alpha_r = 0$, and for $L_{\rm R} = 7.5 \pm 3.7 \times 10^{26}$ erg sec^{-1}, we obtain $L_{\rm kin} \simeq 3.6 \times 10^{35} \mathcal{W}_{37.8}$ erg sec^{-1}, or

$$\frac{L_{\rm kin}}{L_{\rm tot}} \simeq 0.6 \times \mathcal{W}_{37.8} \; y^{-1} \; (\eta/0.1)^{-1} \qquad (6)$$

This would mean that the jet/outflow carries a significant amount of the accretion energy budget away from the system. I so, then any realistic accretion flow model for quiescence shall necessarily incorporate the effects of an outflow both in terms of energetics and dynamics, effectively ruling out a pure ADAF solution.

Using the estimate for the kinetic power of the jet in quiescence given in Equation 5, we can calculate the total energy carried out by it in between outbursts, assuming again that the 58 years recurrence time is not overestimated. We obtain $E_{\rm jet} \simeq 6.6 \times 10^{44} \mathcal{W}_{37.8}$ erg, of the same order of the energy released during an outburst. Interestingly, Meyer-Hofmeister & Meyer (1999) calculated the outburst evolution for A0620−00 with a model accounting for evaporation of the cold outer disc (but neglecting outflows),

[4] Especially considering that that in the mid 40’s, close to World War II, there were no useful Harvard plate archives.

[5] Following the formalism of Heinz & Grimm (2005), the *average* jet ‘efficiency’ W_0 is given by the expression $W_0 \approx 6.2 \times 10^{37} \mathcal{W}_{37.8}$ erg sec^{-1} (see their Equation 10). Here the parameter $\mathcal{W}_{37.8}$, which equals unity if $W_0 = 10^{37.8}$ erg sec^{-1}, is meant to allow the reader to adjust for future improvements and/or preferences in this value. Note however that the normalisation in Equation 5 is very close to that proposed by Fender, Maccarone & van Kesteren 2006 based on different grounds.

and concluded that only about one third of the mass accreted during quiescence need to be stored in the disc for the subsequent outbursting episode.

(ii) Under the **ADIOS** working-hypothesis, the mass flowing from the outer disc does not reach the inner region, but is lost in a outflow. The accretion rate is now a function of radius:

$$\dot{M}(R) = \begin{cases} \dot{M}_{\rm out}, & R_{\rm out} > R > R_{\rm tr} \\ \dot{M}_{\rm out}(R/R_{\rm tr})^{\alpha}, & R_{\rm tr} > R > R_{\rm in} \end{cases} \quad (7)$$

where we have assumed that mass loss sets in within the truncation radius $R_{\rm tr}$. Proceeding as before, we can then estimate the truncation radius for $\dot{M}_{\rm in} = \dot{M}(R_{\rm in}{=}3R_{\rm S})$, being $R_{\rm S}$ the Schwarzschild radius for a 10 $M_{\odot}$ BH. For $\alpha = 1$ we obtain

$$R_{\rm tr} \simeq 1.8 \times 10^4 \; (y/w) \; (\eta/0.1) \; R_{\rm S} \; , \quad (8)$$

or $\simeq 5.4\times10^{10}$ (y/w) $(\eta/0.1)$ cm, to be compared with the orbital separation of about 3×10^{11} cm (Gelino et al. 2001).

If we assume that the the jet/outflow is powered by the mass lost from the accretion flow, then its total kinetic power $L_{\rm kin}$ is given by

$$L_{\rm kin} = L_{\rm tot} \left(1 - \frac{R_{\rm in}}{R_{\rm tr}}\right) \simeq L_{\rm tot}, \quad (9)$$

i.e. in the ADIOS framework, a dominant fraction of the total accretion power is channelled into the jet/outflow.

In spite of the many uncertainties in the above calculations, the jet/outflow kinetic power turns out to be a sizable fraction of $L_{\rm tot}$, effectively ruling out a *pure* ADAF solution for the dynamics of A0620−00 in quiescence.

However, within these uncertainties there is still room for a hybrid solution to apply, one in which at each $\dot{M}$ about half of the energy is carried away by the outflow, while the rest is advected inward and finally added to the BH mass (see e.g. Körding, Fender & Migliari 2006).

5 SUMMARY AND FINAL REMARKS

Deep VLA observations of A0620–00, performed in 2005 August, have provided us with the first radio detection of a quiescent stellar mass BH emitting at X-ray luminosities as low as $L_{\rm Edd} \simeq 10^{-8.5}$. The level of radio emission – 51 μJy at 8.5 GHz – is the lowest ever measured in an X-ray binary. At a distance of 1.2 kpc, this corresponds to a radio luminosity $L_{\rm R} = 7.5 \times 10^{26}$ erg sec^{-1}. By analogy with higher luminosity systems, partially self-absorbed synchrotron emission from a relativistic outflow appears to be the most likely interpretation. Free-free wind emission is ruled out on the basis that far too high mass loss rates would be required, either from the companion star or the accretion disc, to produce observable emission at radio wavelengths, while gyrosynchrotron radiation from the corona of the companion star is likely to contribute to less than 5 per cent to the measured flux density.

A0620−00 was observed simultaneously in the X-ray band with *Chandra*; the 0.3-8 keV spectrum is well fitted by an absorbed power law with photon index $\Gamma = 2.08^{+0.49}_{-0.35}$ and hydrogen equivalent column density consistent with the optical value. The corresponding 2–10 keV luminosity is $L_{\rm X} = 7.1 \times 10^{30}$ erg sec^{-1}, a factor of about two higher than in a previous *Chandra* observation, in February 2000. Combining the spectra of the two *Chandra* observations results in a best-fitting power law photon index $\Gamma = 2.04^{+0.18}_{-0.25}$, not particularly soft with respect to the $\Gamma \simeq 1.7$ characteristic of higher luminosity, hard state BHBs.

The simultaneous *Chandra* observation of A0620−00 allowed us to test and extend the radio/X-ray correlation for BHBs by 3 orders of magnitude in $L_{\rm X}$. The measured radio/X-ray fluxes confirm the existence of a non-linear scaling between the radio and X-ray luminosity in this systems; with the addition of the A0620−00 point $L_{\rm R} \propto L_{\rm X}^{0.58\pm0.16}$ provides a good fit to the data for $L_{\rm X}$ spanning between $10^{-8.5}$ and $10^{-2}L_{\rm Edd}$. The fitted slope, albeit consistent with the previously reported value of 0.7 ± 0.1, is admittedly affected by the uncertainties in the distance to GX339–4, for which the correlation extends over 3 orders of magnitude in $L_{\rm X}$ and holds over different epochs. Pending a more accurate determination of the distance to this source, we can nevertheless exclude the relation breaking down and/or steepening in quiescence.

By making use of the estimate of the outer accretion rate of A0620−00 in quiescence and of the jet radiative efficiency by Heinz & Grimm (2005), we demonstrate directly that the outflow kinetic power accounts for a sizable fraction of the accretion energy budget, and thus must be important with respect to the overall accretion dynamics of the system. If indeed the outflow acts as a primary sink of energy in quiescence, then its effects should be incorporated in the modelling of the underlying accretion flow, favouring ADIOS-like scenarios to pure ADAF models. As envisaged by Livio et al. (2003), it may well be that what is generally interpreted as a physical disc inner radius in the hard and quiescent states, actually corresponds to the transition between the portion of the disc where the bulk of the liberated accretion power is dissipated locally, within the disc-corona system, and the inner portion, where the most of the power is channelled into a relativistic outflow. In other words, the disc only disappears observationally. A qualitatively similar scenario is that proposed by Ferreira et al. (2006), where the central regions of hard/quiescent state BHBs are composed of an outer standard disc and an inner 'jet-emitting disc', driving a MHD jet. It is worth mentioning that global, fully relativistic MHD simulations of accretion tori also result in Poynting flux dominated narrow jets emanating from the innermost regions, surrounded by a wider, baryon-loaded outflow (De Villiers & Hawley 2003).

The radio/X-ray correlation for BHBs has been proven to extend down to the low-mass low-luminosity corner of the so called 'Fundamental Plane of black hole activity' (MHdM03; FKM04), which unites stellar and super-massive BHs in a $\log(L_{\rm R}$-$L_{\rm X}$-$M)$ plane. The A0620−00 data lie on the best fitting 3D correlation, which has thus been extended by more than 2 orders of magnitude in $L_{\rm X}$ and $L_{\rm R}$. While it may be still premature to make use of the plane relation as a conclusive diagnostic of the accretion model, the FP can be read as an observational proof for the scale-invariance of the jet-accretion coupling in accreting black holes spanning the whole range of radio and X-ray luminosities that is observable with current instrumentation.

6 ACKNOWLEDGEMENTS

Support for this work was provided by the National Aeronautics and Space Administration (NASA) through *Chandra* Postdoctoral Fellowship Awards PF5-60037 (E.G.) and PF3-40026 (S.H.), issued by the *Chandra* X-Ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of NASA under contract NAS8-03060. The National Radio Astronomy Observatory is a facility of the National Science Foundation

operated under cooperative agreement by Associated Universities, Inc.. E.G. is grateful to Manuel Güdel for helpful suggestions on the radio properties of magnetic stars. T.M. wishes to thank Elmar Körding for useful discussions.

REFERENCES

Asai K., Dotani T., Hoshi R., Tanaka Y., Robinson C. R., Terada K. 1998, PASJ, 50, 611
Bildsten L., Rutledge R. E. 2000, ApJ, 541, 908
Blandford R. D., Begelman M. C. 2004, MNRAS, 349, 68
Blandford R. D., Begelman M. C. 1999, MNRAS, 303, L1
Blandford R. D., Königl A. 1979, ApJ, 232, 34
Bregman J. N. 2005, ApJL submitted (astro-ph/0511368)
Corbel S., Nowak M., Fender R. P., Tzioumis A. K., Markoff S. 2003, A&A, 400, 1007
Corbel S., Fender R. P., Tzioumis A. K., Nowak M., McIntyre V., Durouchoux P., Sood R. 2000 A&A, 359, 251
Corbel S. et al. 2001, ApJ, 554, 43
Craft H. D., 1975, IAU Circ. 2822
Davis R. J., Edwards M. R., Morison I., Spencer R. E., 1975, Nat, 257, 659
Davis S. W., Blaes O. M., Hubeny I., Turner N. J. 2005, ApJ, 621, 372
De Villiers J.-P., Hawley J. F. 2003, ApJ, 592, 1060
Drake S. A., Simon T., Linsky J. L. 1989, ApJS, 71, 905
Elvis M., Page C. G., Pounds K. A., Ricketts M. J., Turner M. J. L. 1975, Nat, 257, 656
Eachus et al. 1976, ApJ, 203, L17
Falcke H., Biermann P. L. 1999, A&A, 342, 49
Falcke H., Biermann P. L. 1996, A&A 308, 321
Falcke H., Biermann P. L. 1995, A&A 293, 665
Falcke H., Körding E., Markoff S. 2004, A&A, 414, 895 (FKM03)
Fender R. P. 2006, in Lewin W. H. G., van der Klis M., eds, Compact Stellar X-Ray Sources. Cambridge Univ. Press, Cambridge
Fender R. P. 2001, MNRAS, 322, 31
Fender R. P., Belloni T. 2004, ARA&A, 42, 317
Fender R. P., Maccarone T. J., van Kesteren Z. 2006, MNRAS, 360, 1085
Fender R. P., Belloni T., Gallo E. 2004, MNRAS, 355, 1105
Fender R. P., Gallo E., Jonker P. G. 2003, MNRAS, 343, L99
Fender R. P., Hjellming R. M., Tilanus R. P. J., Pooley G. G., Deane J. R., Ogley R. N., Spencer R. E. 2001, 322, L23
Ferreira J., Petrucci P. O., Henri G., Sauge L., Pelletier G. 2006, 447, 813
Gallo E., Fender R. P., Hynes R. I. 2005, MNRAS, 356, 1017
Gallo E., Fender R. P., Pooley G. G. 2003, MNRAS, 344, 60 (GFP03)
Gallo E., Fender R. P., Kaiser C., Russell D., Morganti R., Osterloo T., Heinz S. 2005, Nat, 436, 819
Garcia M. R., McClintock J. E., Narayan R., Callanan P., Barret D., Murray S. S. 2001, ApJ, 553, L47
Gelino D. M., Harrison T. E., Orosz J. E. 2001, AJ, 122, 2668
Giannios D. 2005, A&A, 437, 1007
Greene J. E., Ho L. C., Ulvestad J. S. 2006, ApJ, 56
Güdel M. 2002, ARA&A, 40, 217
Hameury J.-M., Barret D., Lasota J.-P., McClintock J. E., Menou K., Motch C., Olive J.-F., Webb N. 2003, A&A, 399, 631
Heinz S. 2004, MNRAS, 355, 835
Heinz S. & Grimm H.-J. 2005, ApJ, 633, 384
Heinz S., Sunyaev R. A. 2003, MNRAS, 343, L59
Homan, J.; Belloni T. 2005, in From X-ray Binaries to Quasars: Black Hole Accretion on All Mass Scales, ed. T. J. Maccarone, R. P. Fender, L. C. Ho (Dordrecht: Kluwer)
Hjellming R. M., Han X. 1995, in X-ray binaries, eds. Lewin W. H. G., van Paradijs J., van den Heuvel E. P. J., Cambridge University Press, Cambridge
Hjellming R. M, Johnston K. J. 1988, ApJ, 328, 600
Huynh M. T., Jackson C. A. Norris R. P. Prandoni I. 2005, AJ, 130, 1373
Hynes R. I., Robinson E. L., Bitner M. 2005, MNRAS, 630, 405
Hynes R. I., Steeghs D., Casares J., Charles P. A., O'Brien K. 2004b, ApJ, 609, 317
Hynes R. I. et al. 2004a, ApJ, 611, L125
Ichimaru S. 1977, ApJ, 214, 840
Jonker P., Nelemans G. 2004, MNRAS, 354, 355
Jonker P., Gallo E., Dhawan V., Rupen M., Fender R. P., Dubus, G. 2004, MNRAS, 351, 1359
Kaiser C. R. 2006, MNRAS, 367, 1083
Kanbach G., Straubmeier C., Spruit H., Belloni T. 2001, Nat, 414, 180
Körding E., Fender R. P., Migliari S. 2006, MNRAS, in press (astro-ph/0603731)
Körding E., Falcke H., Corbel S. 2006, A&A, in press (astro-ph/0603117)
Kong A. K. H., McClintock J. E., Garcia M. R., Murray S. S., Barret D. 2002 ApJ, 570, 277
Lim J., White S. M., Nelson G. J., Benz A. O. 1994, ApJ, 430, 322
Liu Q. Z., van Paradijs J., van den Heuvel E. P. J. 2001, A&A 368, 1021
Livio M., Pringle J. E., King A. R. 2003, ApJ, 593, 184
Maccarone T. J. 2005, MNRAS, 364, 971
Maccarone T. J., Coppi P. 2003, MNRAS, 338, 189
Maccarone T. J., Gallo E., Fender R. P. 2003, MNRAS, 345, L19
Malzac J., Belloni T., Spruit H. C., Kanbach G. 2003, A&A, 407, 335
Markoff S. 2005, ApJ, 618, L103
Markoff S., Nowak M. A. 2004, ApJ, 609, 972
Markoff S., Nowak M. A., Wilms J. 2005, 635, 1203
Markoff S., Falcke H., Fender R. 2001, A&A, 372, L25
Marsh T. R., Robinson E. L., Wood J. H. 1994, MNRAS, 266, 137
Meier D. L. 2001, ApJ, 548, L9
Merloni A., Fabian A. C. 2002, MNRAS, 332, 165
Merloni A., Heinz S., Di Matteo T. 2003, MNRAS, 345, 1057 (MHdM03)
Merloni A., Körding E., Heinz S., Markoff S., Di Matteo T., Falcke H. 2006, New Astronomy submitted (astro-ph/0601286)
Mirabel I. F., Rodríguez L. F. 1999, ARA&A, 37, 409
Mirabel I. F., Rodríguez L. F., Cordier B., Lebrun F. 1992, Nat, 358, 215
Mirabel I. F., Rodríguez L. F., Cordier B., Paul J., Lebrun F. 1993, A&ASS, 97, 193
McClintock J. E. & Remillard R. A. 2006, in Lewin W. H. G., van der Klis M., eds, Compact Stellar X-Ray Sources. Cambridge Univ. Press, Cambridge
McClintock J. E., Narayan R., Rybicki G. B. 2004, ApJ, 615, 402
McClintock J. E., Horne K., Remillard R. A. 1995, ApJ, 442, 358
McClintock J. E., Narayan R., Garcia M. R., Orosz J. A., Remillard R. A., Murray S. S. 2003, ApJ, 593, 435
McClintock J. E. et al. , 1983, ApJ, 266, L27
Meyer-Hofmeister E. & Meyer F. 1999, A&A, 348, 154
Migliari S., Fender R. P. 2006, MNRAS, 366, 79
Narayan R., Yi I. 1995, ApJ, 452, 710
Narayan R., Yi I. 1994, ApJ, 428, L13
Narayan R., Igumenshchev I. V., Abramowicz M. A. 2000, ApJ, 539, 798
Narayan R., Barret D., McClintock J. E. 1997, ApJ, 482, 448
Narayan R., Garcia M. R., McClintock J. E. 1997, ApJ, 478, L79
Narayan R., McClintock J. E., Yi I. 1996, ApJ, 457, 821
Owen F. N., Balonek T. J., Dickey J., Terzian Y., Gottesman S. T. 1976, ApJ, 203, L15
Pal S., Chakrabarti S. K. 2004, A&A 421, 13
Predehl P., Schmitt J. H. M. M., 1995, A&A, 293, 889
Quataert E., Gruzinov A. 2000, ApJ, 539, 809
Robertson S. L., Leiter D. J. 2004, MNRAS, 350, 1391
Robinson R. D., Carpenter K. G., Slee O. B., Nelson G. J., Stewart R. T. 1994, MNRAS, 267, 218
Shahbaz T., Naylor T., Charles P. A. 1994, MNRAS, 268, 756
Shahbaz, T. et al. 2004, MNRAS, 354, 31
Shakura, N. I.; Sunyaev, R. A. 1973, A&A, 24, 337-355
Tomsick J. et al. , 2003, ApJ, 597L, 133
Yuan F., Cui W., 2005, ApJ, 629, 408
Yuan F., Cui W., Narayan R. 2005, ApJ, 620, 905
Huang M., Wheeler J. C. 1989, ApJ, 343, 229
Warner B. 1987, MNRAS, 227, 23
Zdziarski A. A., Lubiński P., Gilfanov M., Revnivtsev M. 2003, MNRAS, 342, 355